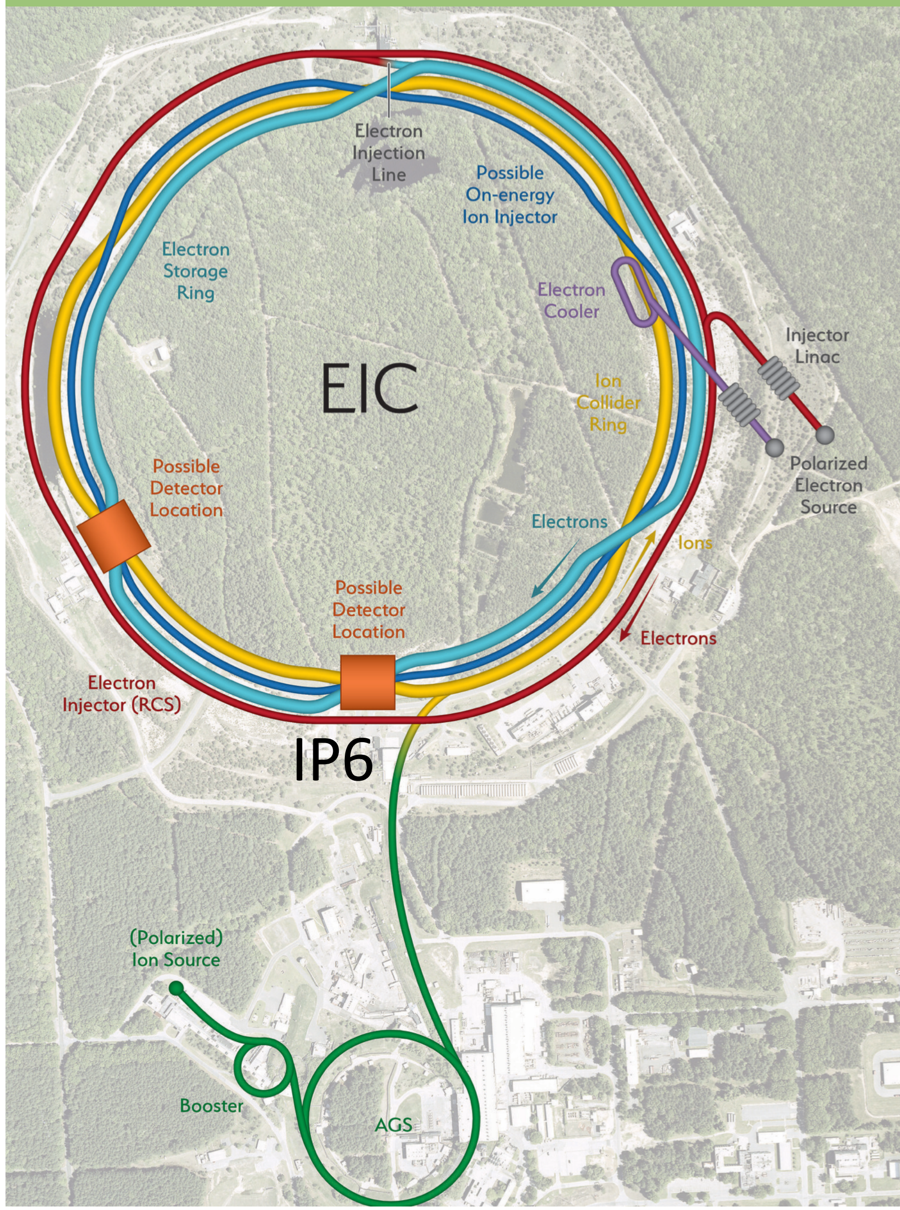
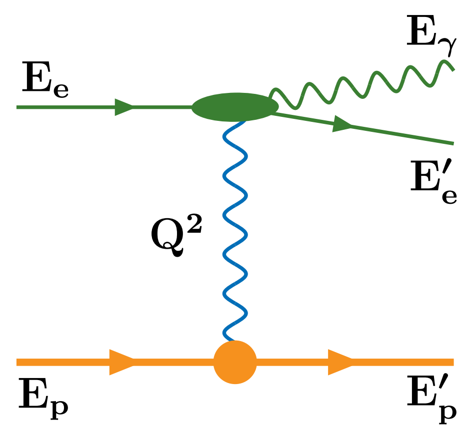
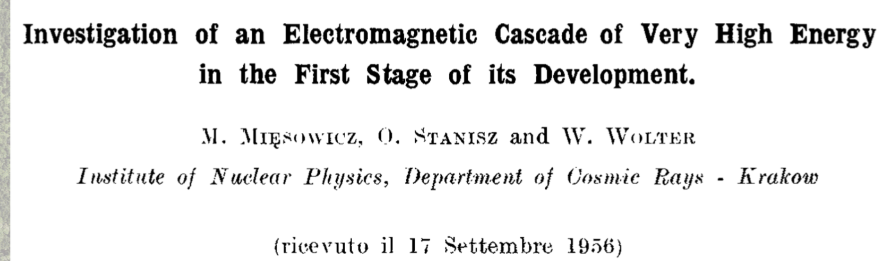
Extreme Photon Interactions at the Electron Ion Collider



Krzysztof PIOTRZKOWSKI – CP³ Center at *UCLouvain*




Investigation of an Electromagnetic Cascade of Very High Energy in the First Stage of its Development.

M. Mięsowicz, O. Stanisz and W. Wolter

Institute of Nuclear Physics, Department of Cosmic Rays - Krakow

(ricevuto il 17 Settembre 1956)

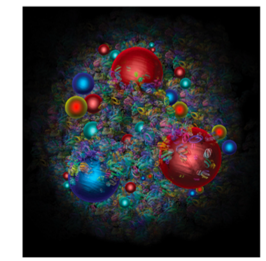
EIC's central aim is to understand better nucleon's internal structure.

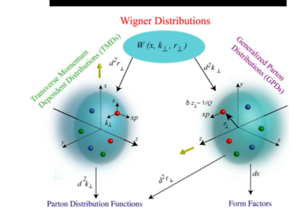
This has various aspects:

- how the quarks and gluons move inside the nucleon,
- 3D imaging of the nucleon – "hadron tomography",
- role of gluons and their emergent properties,
- how is spin decomposed,
- origin of nucleon mass,
- . . .

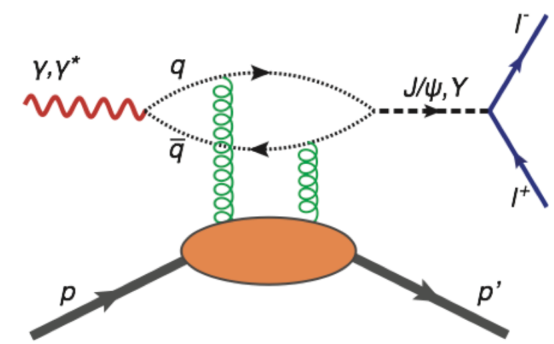
Lattice can provide *qualitative* and eventually *quantitative* knowledge of different functions and their moments:

- 1D: form factors
- 1D: parton distribution functions (PDFs)
- 3D: generalized parton distributions (GPDs)
- 3D: transverse momentum dependent PDFs (TMDs)
- 5D: Wigner function





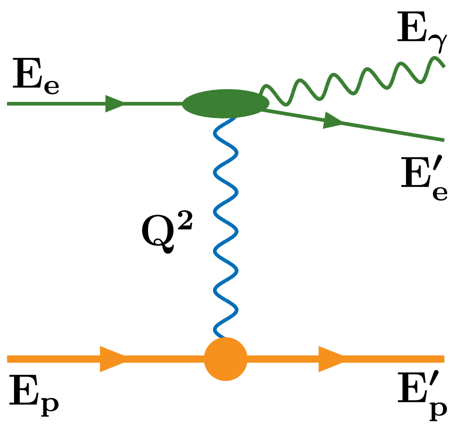
"EIC@IP6"



EIC Seminar

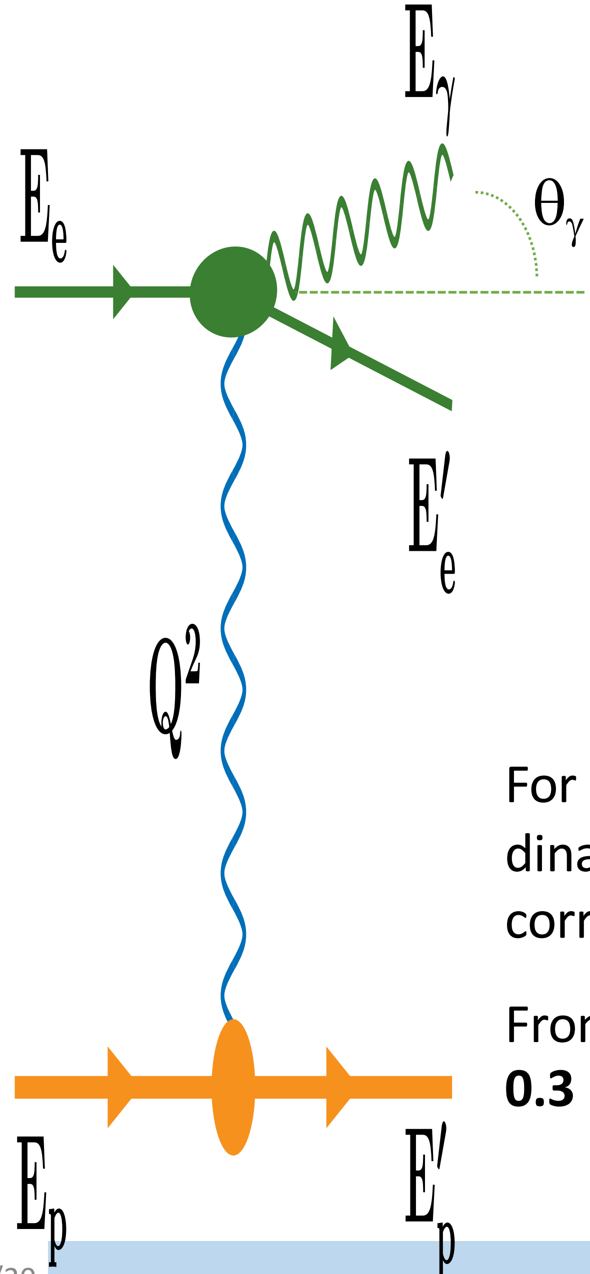
March 15, 2021

Bremsstrahlung (at high energy) is truly unique



Bremsstrahlung process was first studied already in 1934 by *Hans Bethe* and *Walter Heitler* – hence the Bethe-Heitler reference still used today – however, its "macroscopically" long-range nature has been elusive ever since…

Example: *ep* bremsstrahlung at high energy



electron-proton bremsstrahlung $\boldsymbol{e + p \rightarrow e' + \gamma + p}$ has following signatures:

$E'_e + k_\gamma = E_e$ to a very (very) high accuracy, and it is a truly "zero-angle process"

⇒ typ. polar angles for photons/scattered electrons, $\theta_\gamma \approx \theta_e \approx m_e/E_e$

It is kinematically allowed that $\theta_\gamma = \theta_{e'} = \theta_p = 0$ – hence there is no transverse momentum transfer, which results in (for variables in LAB):

$$|q_{min}| = m_e^2\, m_p\, E_\gamma/(4\, E_p\, E_e\, E'_e),$$ where

$$Q^2 = -q^2 \approx -q^2{}_{min} + q_T{}^2$$

For example, at the EIC, for $E_e = 18$ GeV, $E_p = 275$ GeV and $E_\gamma = 1$ GeV, one gets the longitudinal momentum transfer, *in the proton rest-frame*, $\Delta p_z = |q_{min}|/c = 0.00073$ eV/c ! The corresponding (kinetic) energy transfer = $(\Delta p)^2/2M \approx 3.10^{-16}$ eV!

From the uncertainty principle it corresponds to the longitudinal distance $\approx \hbar/\Delta p_z$ of **0.3 mm** whereas in the transverse plane the impact parameters can be even larger!

Higher beam energies/lower photon energy ⇒ **more** extreme it becomes!

High energy bremsstrahlung – coherence loss

This long-range character of bremsstrahlung has spectacular consequences:

$\Delta p_z \rightarrow$ *Landau-Pomeranchuk-Migdal effect** and dielectric/*Ter-Mikaelian effect*** & other "environmental" effects as strong magnetic fields – all that due to extremely small **longitudinal** momentum transfers.

The notion of a coherence length (often called the *formation length* in this context) is introduced – bremsstrahlung is **suppressed**, when the electrons/photons are "perturbated during interaction", leading to *coherence loss.* In dense media bremsstrahlung is not a "binary" process anymore.

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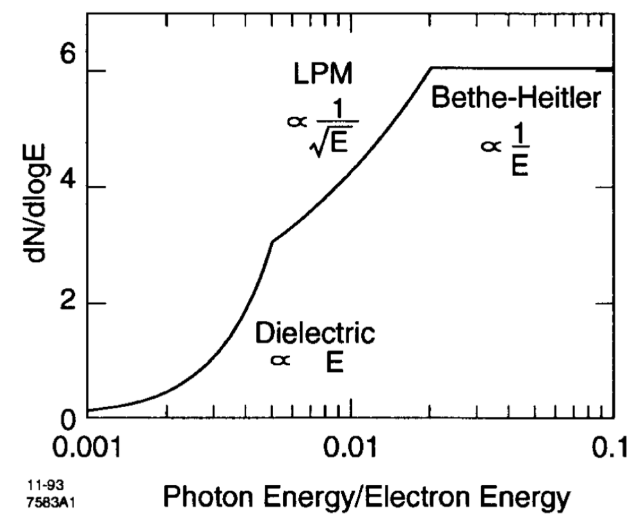


*) L.D. Landau & I. Pomeranchuk (1953) "Limits of applicability of the theory of bremsstrahlung electrons and pair production at high-energies", *Dokl. Akad. Nauk S. F.* **92**; A.B. Migdal (1956) "Bremsstrahlung and pair production in condensed media at high-energies", *Phys. Rev.* **103**: 1811.
) M.L. Ter-Mikaelian (1954), *Dokl. Akad. Nauk Ser. Fiz.* **94: 1033.

LPM effect and formation length for UHECR

LPM effect for bremsstrahlung was studied at SLAC only in 1990s, but LPM also affects VERY high-energy photon pair production:

Ultra-High-Energy Cosmic Ray is a cosmic ray with an energy greater than 1 EeV = 10^{18} eV, for such photon energies its interactions in medium are extremely distorted ⇒

https://pdg.lbl.gov/2020/reviews/rpp2020-rev-passage-particles-matter.pdf
https://doi.org/10.1103/PhysRevD.82.074017

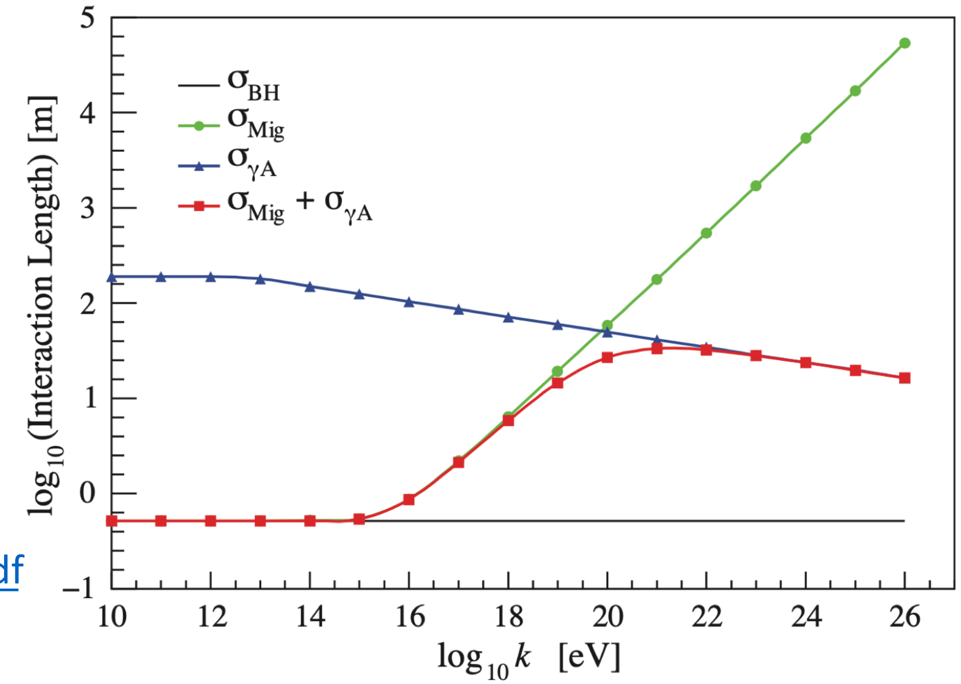


Figure 34.19: Interaction length for a photon in ice as a function of photon energy for the Bethe-Heitler (BH), LPM (Mig) and photonuclear (γA) cross sections [57]. The Bethe-Heitler interaction length is $9X_0/7$, and X_0 is 0.393 m in ice.

Formation length l_f for the electron bremsstrahlung = $2\hbar c\gamma_e^2/E_\gamma = 2\hbar c\gamma_e/m_e r_\gamma$ where γ_e is the electron Lorentz factor.

For example, if E_e = 50 EeV and $r_\gamma = E_\gamma/E_e$ = 1 (0,001) % one gets **l_f = 4 (4000) km!**

Bremsstrahlung at HERA: Observation of Beam Size Effect

$$d^3\sigma/dE_\gamma d\theta_e d\theta_\gamma \propto Q^{-4}$$

hence the cross-section integrated over angles, that is the bremsstrahlung spectrum, is dominated by large distance contributions

$p_T = 0 \rightarrow$ infinite impact parameter!

$p_{T,typ} \approx |q_{min}|/c \rightarrow$ **Beam-Size Effect** - *effective* bremsstrahlung *suppression* at colliders, at low E_γ, due to finite beam-sizes

At HERA I, for E_γ = 1 GeV $|q_{min}| \approx$ 0.0001 eV $\Rightarrow$ it corresponded to a 2 mm impact parameter, whereas the HERA colliding beam lateral sizes $\ll$ 1 mm

Nota bene: This has nothing to do with the "environmental effects" – it is present in proper "binary" processes

It effectively comes from the ("text-book") **definition** of a cross-section:

Event rate = Luminosity × σ

where colliding particles are represented by PLANE waves **but** this *assumption* breaks down if the lateral beam sizes are **comparable** to the relevant impact parameter of a process!

Bremsstrahlung at HERA: Observation of Beam Size Effect

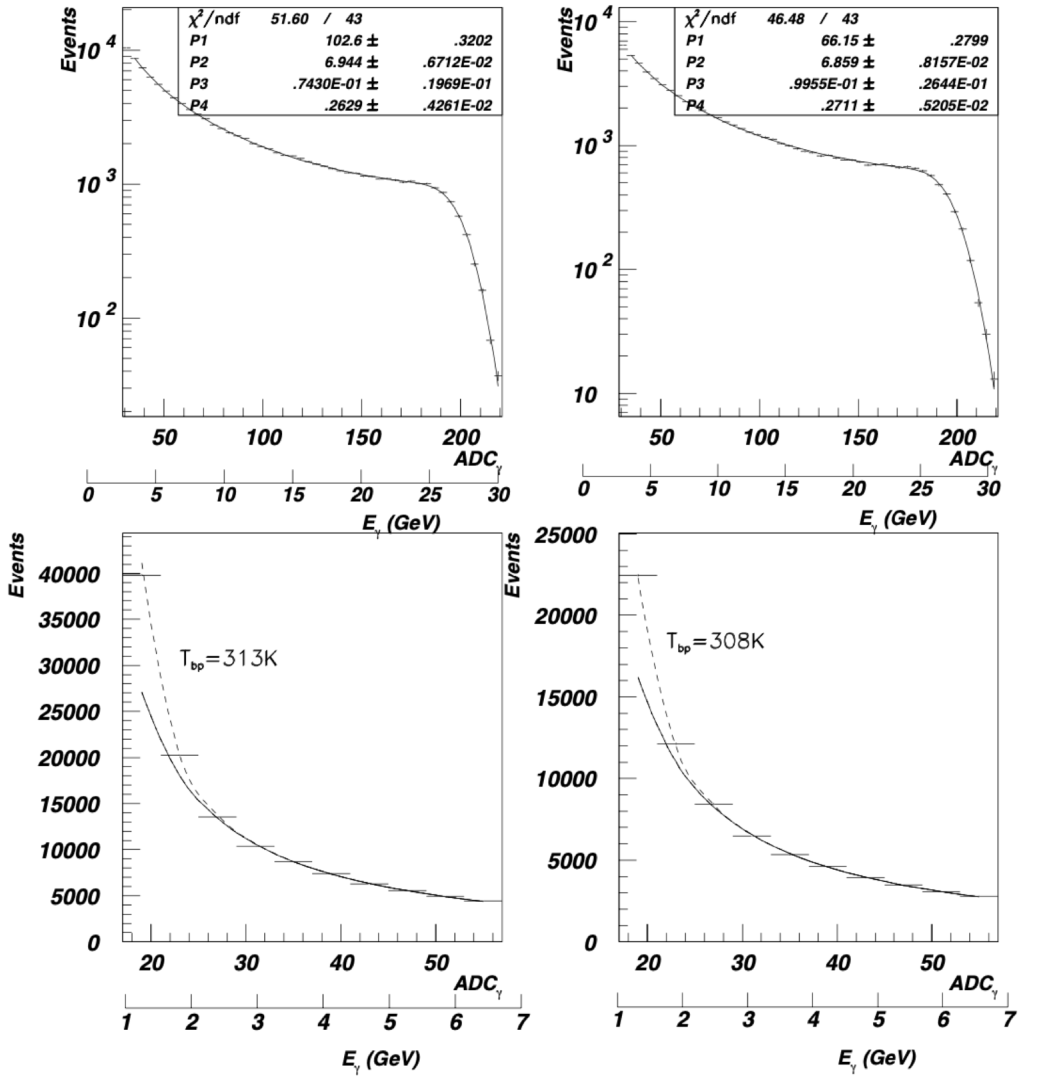
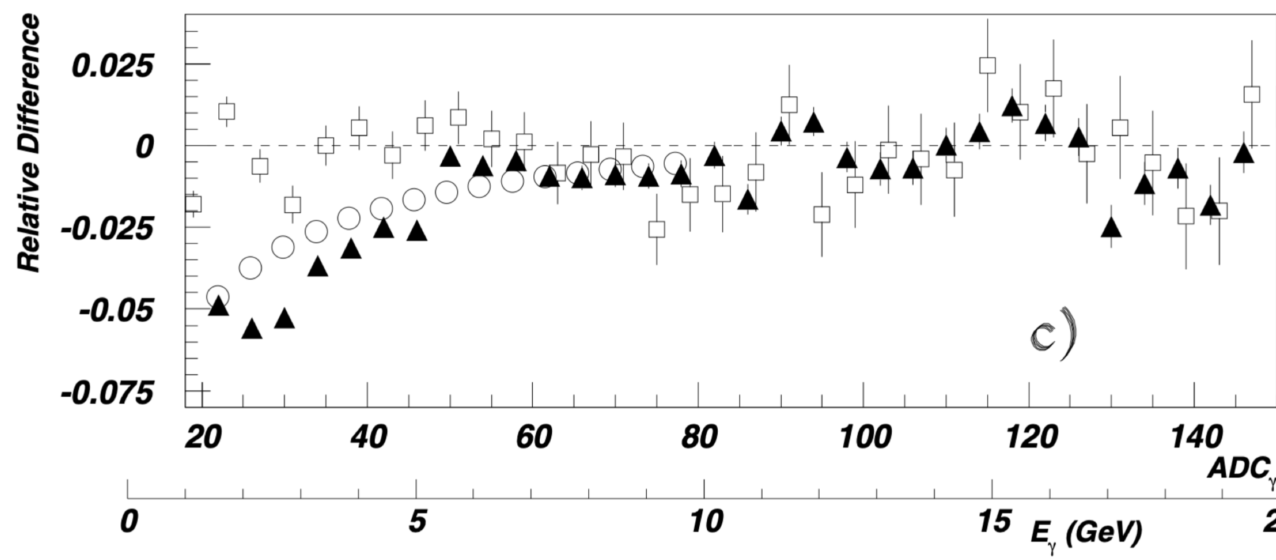


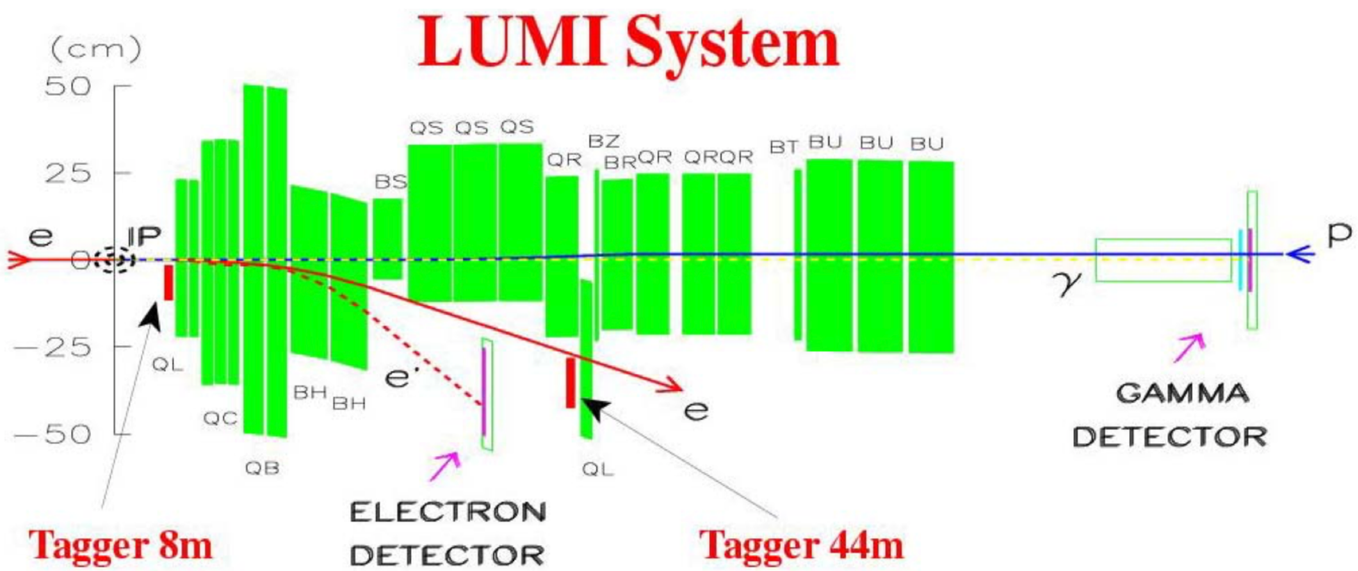
Figure 3: Two spectra of eN bremsstrahlung measured in the luminosity monitor using the electron pilot bunches. The histograms represent the data and the curves are results of fitting the function F (from Eq.1) for $E_\gamma > 3.5$ GeV; in the lower plots the low energy parts of the spectra are shown with extrapolations of the curves obtained from the fits - the excess of events with $2 > E_\gamma > 1$ GeV is well described by adding a contribution from Compton scattering of the blackbody photons off the beam electrons (dashed curves, T_{bp} is the beam-pipe temperature).

K. Piotrzkowski, Zeit. für Physik C **67** (1995) 577,
https://arxiv.org/abs/hep-ex/9504003

electron-gas bremsstrahlung was measured to agree with the Bethe-Heitler LO formula but a significant suppression of *electron-proton* bremsstrahlung was observed at low photon energies – it was found to agree at 30% level with the BSE calculations by G. Kotkin *et al.*, Z. Phys. C **39**, 61 (1988):



ep bremsstrahlung: luminosity measurement at HERA I



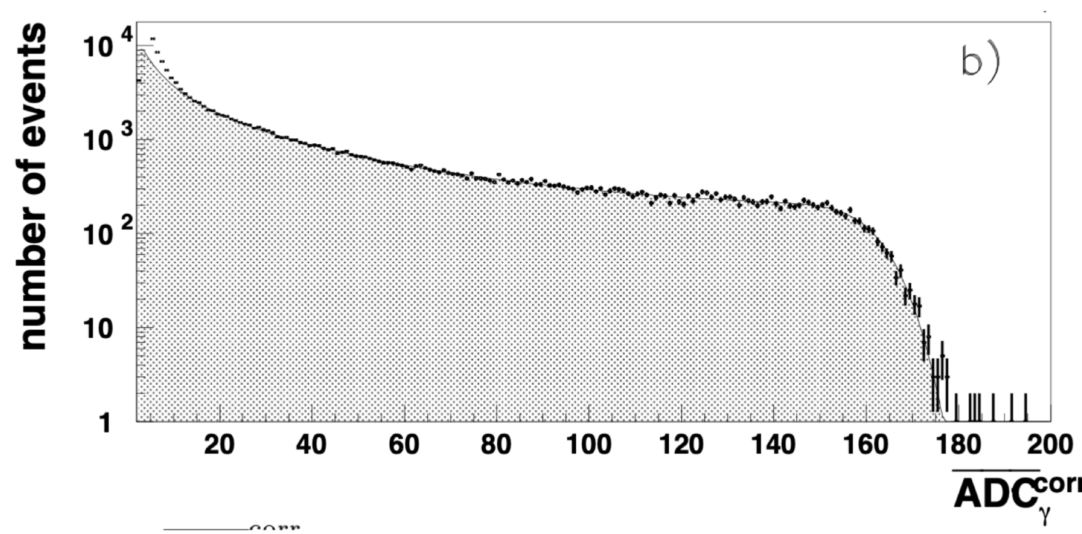
TOP view

ZEUS LUMI consortium: IFJ + AGH + DESY

Acta Phys. Polon. B **32** (2001) 2025

27.5 GeV $e \times 820$ GeV p

Acceptance error	0.8%
Cross section calculation	0.5%
e gas background substr.	0.1%
Multiple event correction	0.03%
Energy scale error	0.5%
Total error	1.05%



Predicted coherent bremsstrahlung (CBS) at HERA

At HERA I, for $E_\gamma = 10$ keV, $\hbar/\Delta p_z \approx$ **11 cm** at LAB $\Rightarrow$ the beam electron interacts with the **whole** proton bunch and the event rate becomes proportional to **number of protons squared**! Hence an extraordinary signal **amplification**.

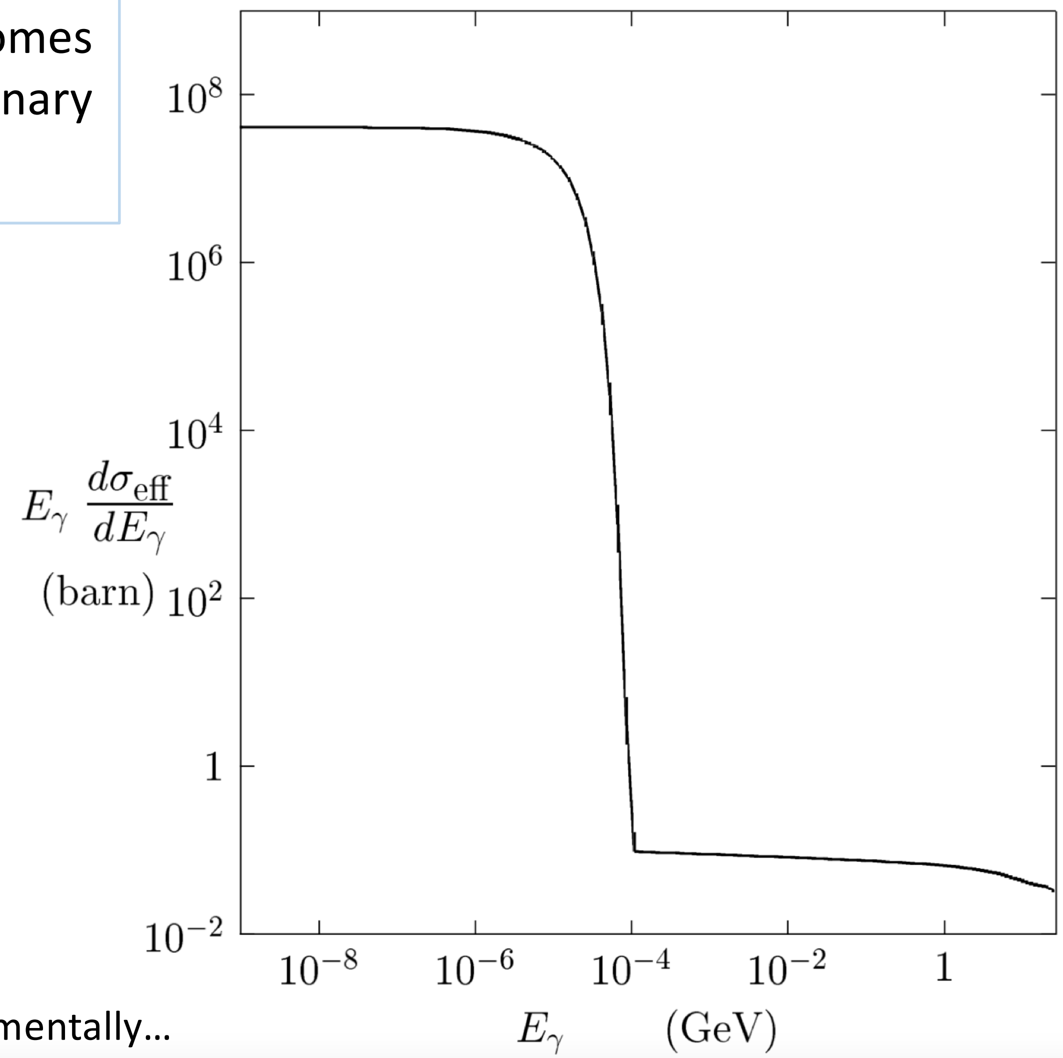
The equivalent photon approximation for coherent processes at colliders

R. Engel, A. Schiller & V. G. Serbo

Zeitschrift für Physik C Particles and Fields **71**, Article number: 651 (1996) | Cite this article

Abstract

We consider coherent electromagnetic processes for colliders with short bunches, in particular the coherent bremsstrahlung (CBS). CBS is the radiation of one bunch particles in the collective field of the oncoming bunch. It can be a potential tool for optimizing collisions and for measuring beam parameters. A new simple and transparent method to calculate CBS is presented based on the equivalent photon approximation for this collective field. The results



It has **same** origin as famous *beamstrahlung,* yet was never confirmed experimentally…

EIC luminosity challenge: electron-ion bremsstrahlung

Precise cross-section measurements are the corner stone of the physics program at the EIC, hence very demanding requirements for its luminosity measurement:

- Absolute $\mathcal{L}$ precision better than 1%
- Bunch-to-bunch relative measurements with very high precision of $\delta\mathcal{L}/\mathcal{L} \approx 10^{-4}$

Old (HERA) recipe: very precisely measure rate *R* of a process with very well known cross-section and use the basic "definition relation" $R = \mathcal{L}\,\sigma$

Best candidate: ***electron-ion* bremsstrahlung,** $e + i \rightarrow e' + \gamma + i$

- (very) large cross-sections (**$\propto Z^2$**), with very small HO corrections
- σ_{brems} is *insensitive* to the beam polarizations
- unique signatures:
  $E_{e'} + E_\gamma = E_e$ to a very high accuracy
  truly "zero-angle process"

OK, but what about the beam-size effect?

In addition: the EIC *ep* luminosity will be almost **1000 times bigger** than that at HERA I, thanks to almost 10 times smaller bunch spacing the event pileup will be partially mitigated but still will be large even for *ep* collisions; **the event pileup scales roughly as Z^2/A** hence for the *eAu* case instead of 10 hard photons every 10 ns more than 100 will hit detectors, what corresponds to **> 10 GHz total event rate**!

Letter Open Access

When invariable cross sections change: The Electron-Ion Collider case

Krzysztof Piotrzkowski and Mariusz Przybycien
Phys. Rev. D **103**, L051901 – Published 5 March 2021

Article | References | No Citing Articles | Supplemental Material | PDF | HTML | Export Citation

ABSTRACT

In everyday research, it is tacitly assumed that scattering cross sections have fixed values for a given particle species, center-of-mass energy, and particle polarization. However, this assumption has been called into question after several observations of suppression of high-energy bremsstrahlung. This process will play a major role in experiments at the future Electron-Ion Collider, and we show how variations of the bremsstrahlung cross section can be profoundly studied there using the lateral beam displacements. In particular, we predict a very strong increase of the observed cross sections for large beam separations. We also discuss the relation of these elusive effects to other quantum phenomena occurring over macroscopic distances. In this context, spectacular and possibly useful properties of the coherent bremsstrahlung at the Electron-Ion Collider are also evaluated.

BSE @ EIC

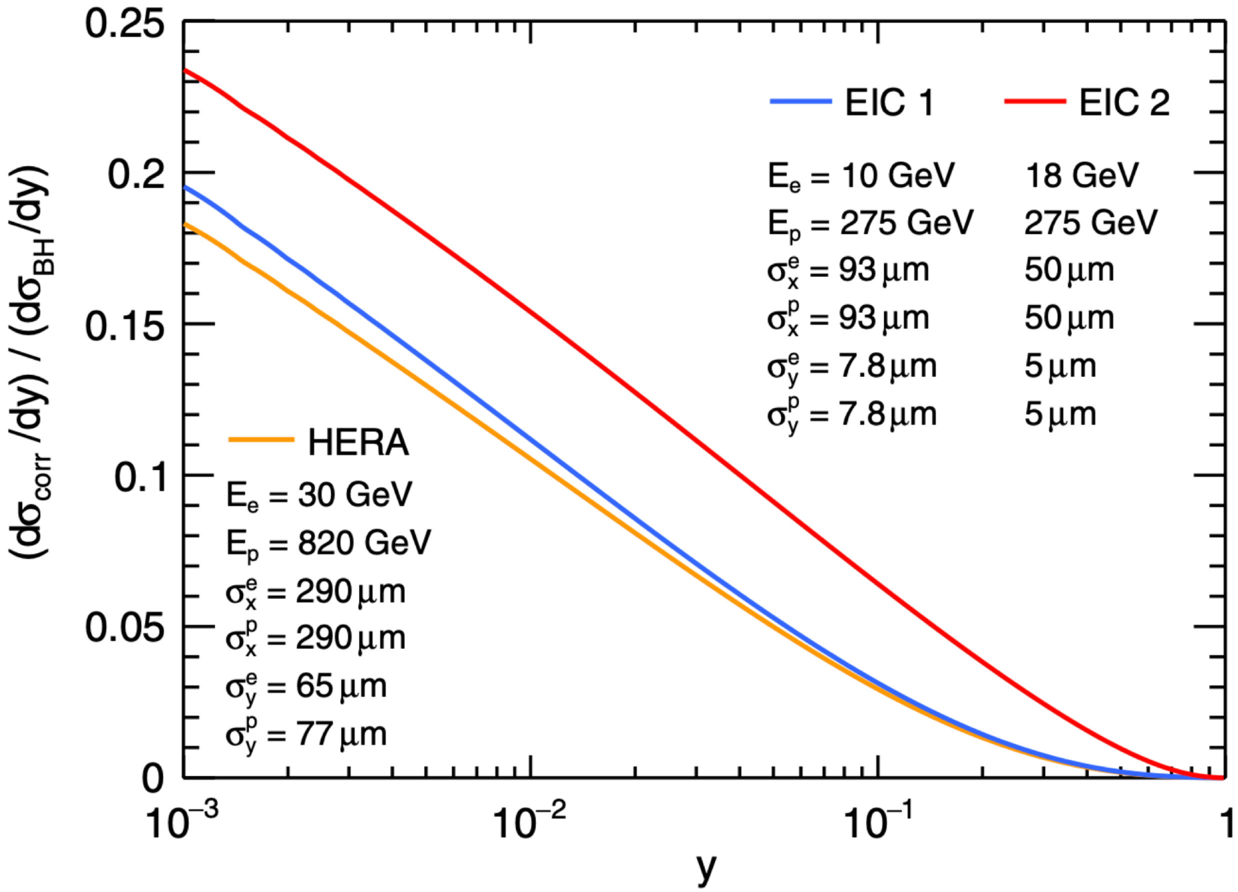


FIG. 2. Relative corrections to the standard Bethe-Heitler cross sections due to the beam-size effect. Relative suppression due to the beam-size effect $(d\sigma_{\text{corr}}/dy)/(d\sigma_{\text{BH}}/dy)$ is shown as a function of $y = E_\gamma/E_e$ for three cases of electron-proton bremsstrahlung.

https://doi.org/10.1103/PhysRevD.103.L051901

Due to very small **vertical** beam sizes bremsstrahlung suppression at the EIC is **stronger** than at HERA – BSE has to be carefully studied and understood to get the required precision on the EIC luminosity

BSE @ EIC

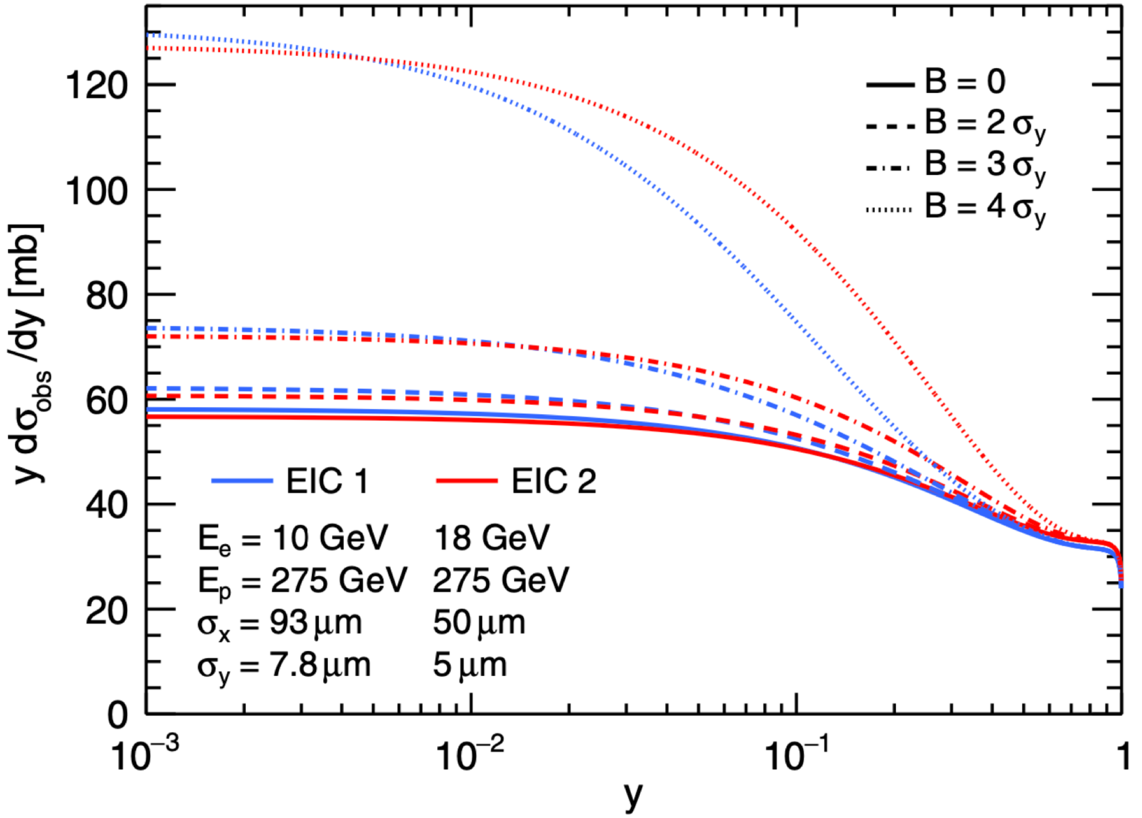


FIG. 4. The predicted spectra of ep bremsstrahlung at the EIC for several vertical beam displacements. The standard Bethe-Heitler cross section $d\sigma_{\mathrm{BH}}/dy$ is modified due to the beam-size effect and beam displacements B. The effective cross sections (multiplied by y for better visibility) are shown for two cases of electron-proton collisions at the EIC—the corresponding beam energies and Gaussian lateral beam sizes at the interaction point are listed.

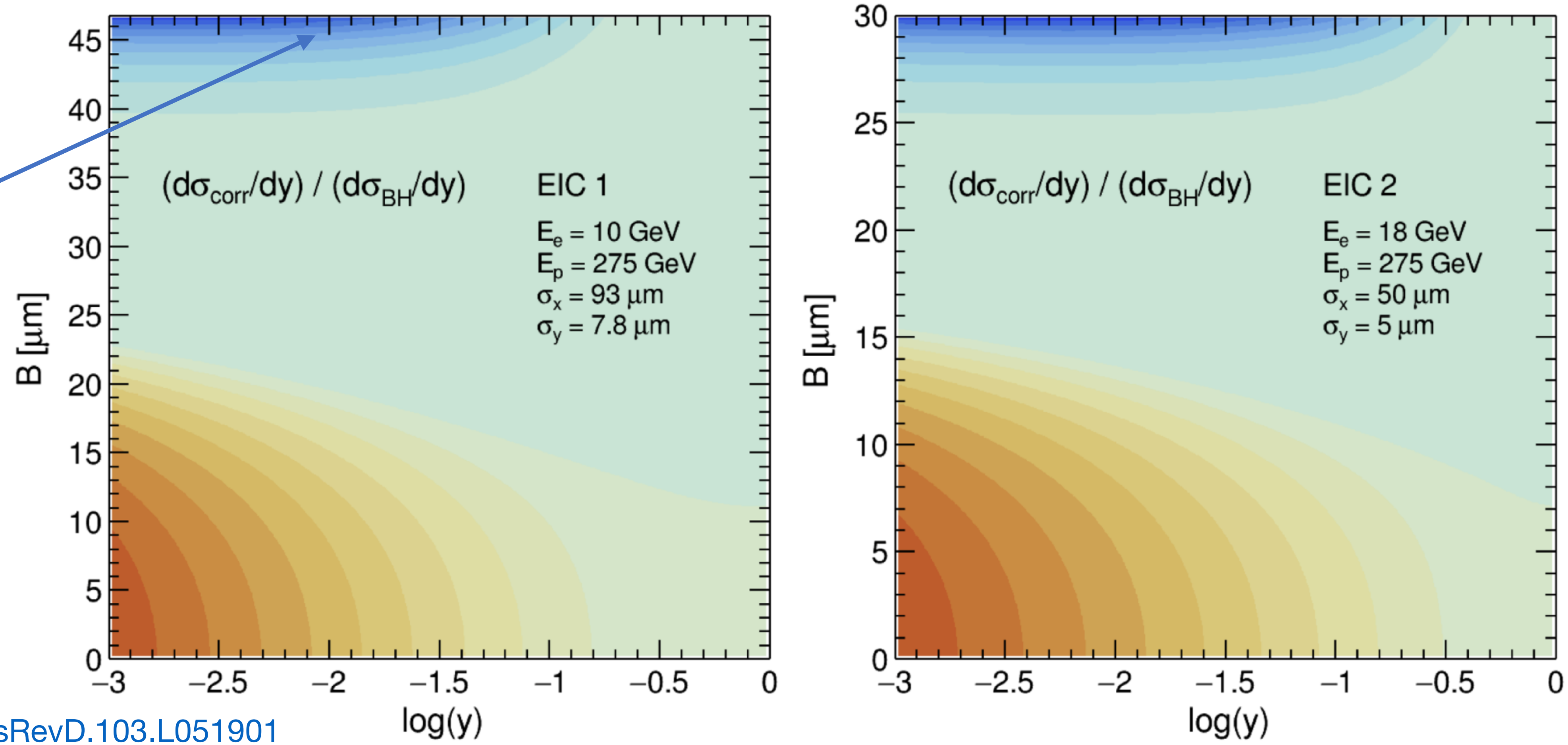
https://doi.org/10.1103/PhysRevD.103.L051901

We propose an original and powerful test of the BSE by measuring the bremsstrahlung spectrum while scanning (vertically) the beams.

This will be at the same time an exciting direct study/demonstration of very long-range nature of bremsstrahlung process – for large **lateral** beam displacements we predict a strong **effective increase** of its cross-section!

BSE @ EIC

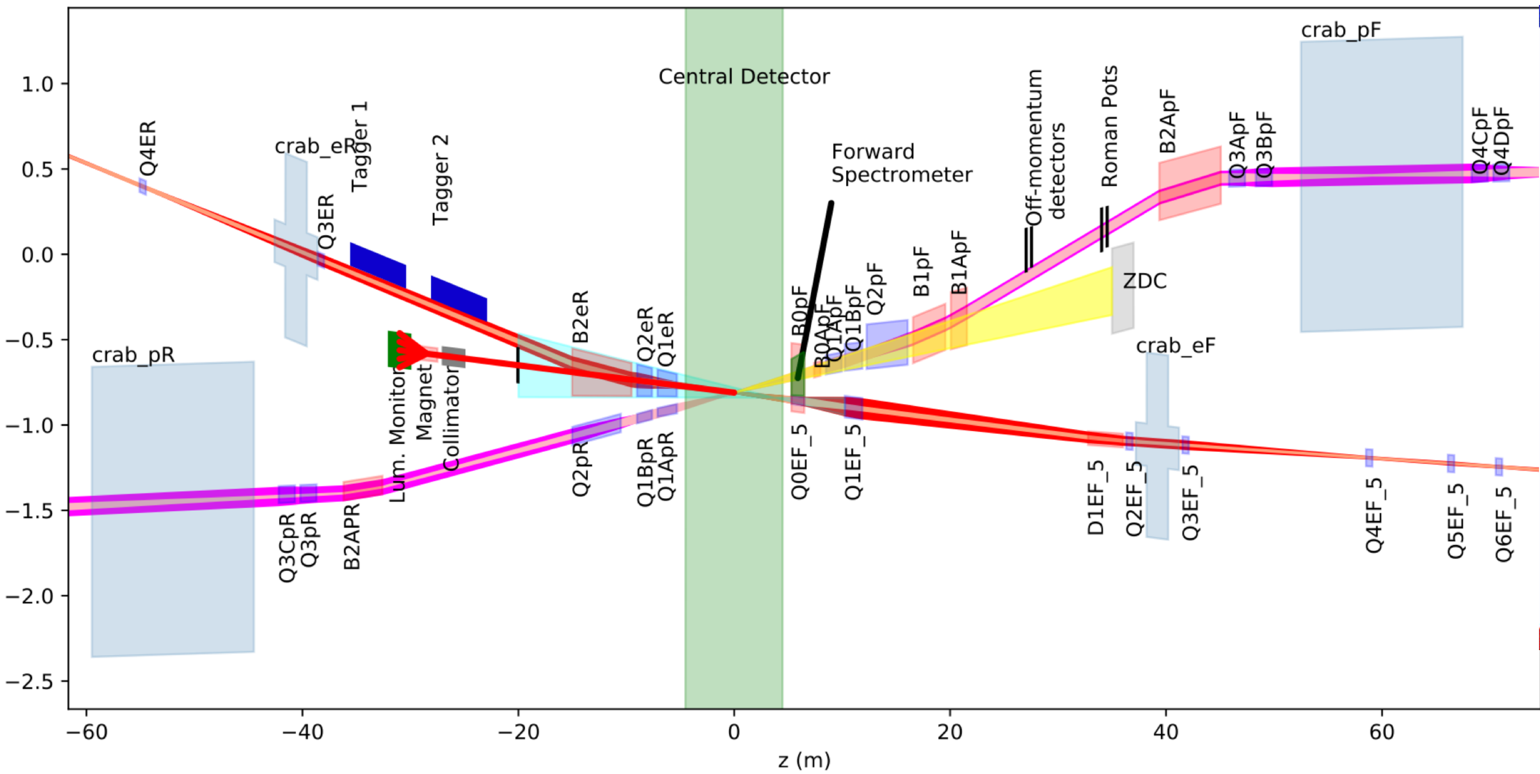
σ × 80

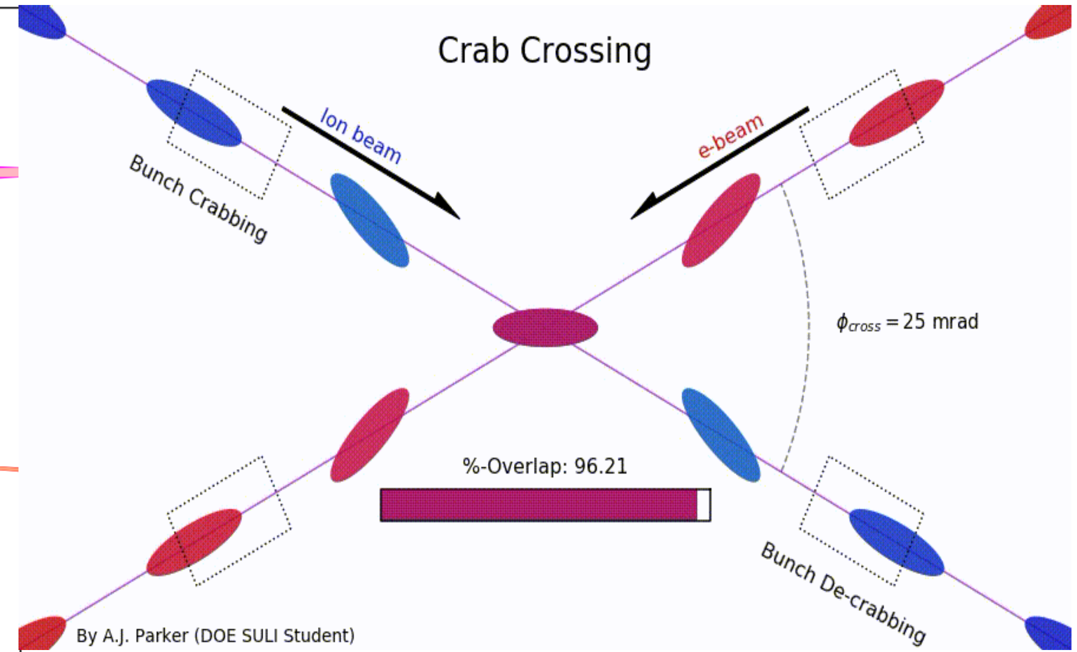


https://doi.org/10.1103/PhysRevD.103.L051901

FIG. 5. Relative corrections to the standard Bethe-Heitler cross sections, due to both the beam-size effect and vertical beam displacements, as a function of B and y. The ratios $(d\sigma_{\rm corr}/dy)/(d\sigma_{\rm BH}/dy)$ are shown as a function of the vertical beam displacement B and the logarithm of the relative photon energy $y = E_\gamma/E_e$ for the two sets of EIC parameters: EIC 1 and EIC 2. The corresponding beam energies and Gaussian lateral beam sizes at the interaction point are listed. Shown are ten equidistant (in the third dimension) contours for the values above zero (displayed in brown) and ten equidistant contours for values below zero (displayed in blue). For the EIC 1 case, the distribution extends in the third dimension between approximately −84 and +0.2, whereas for the EIC 2 case this range spans approximately from −80.5 to +0.24.

Luminosity measurements at the EIC

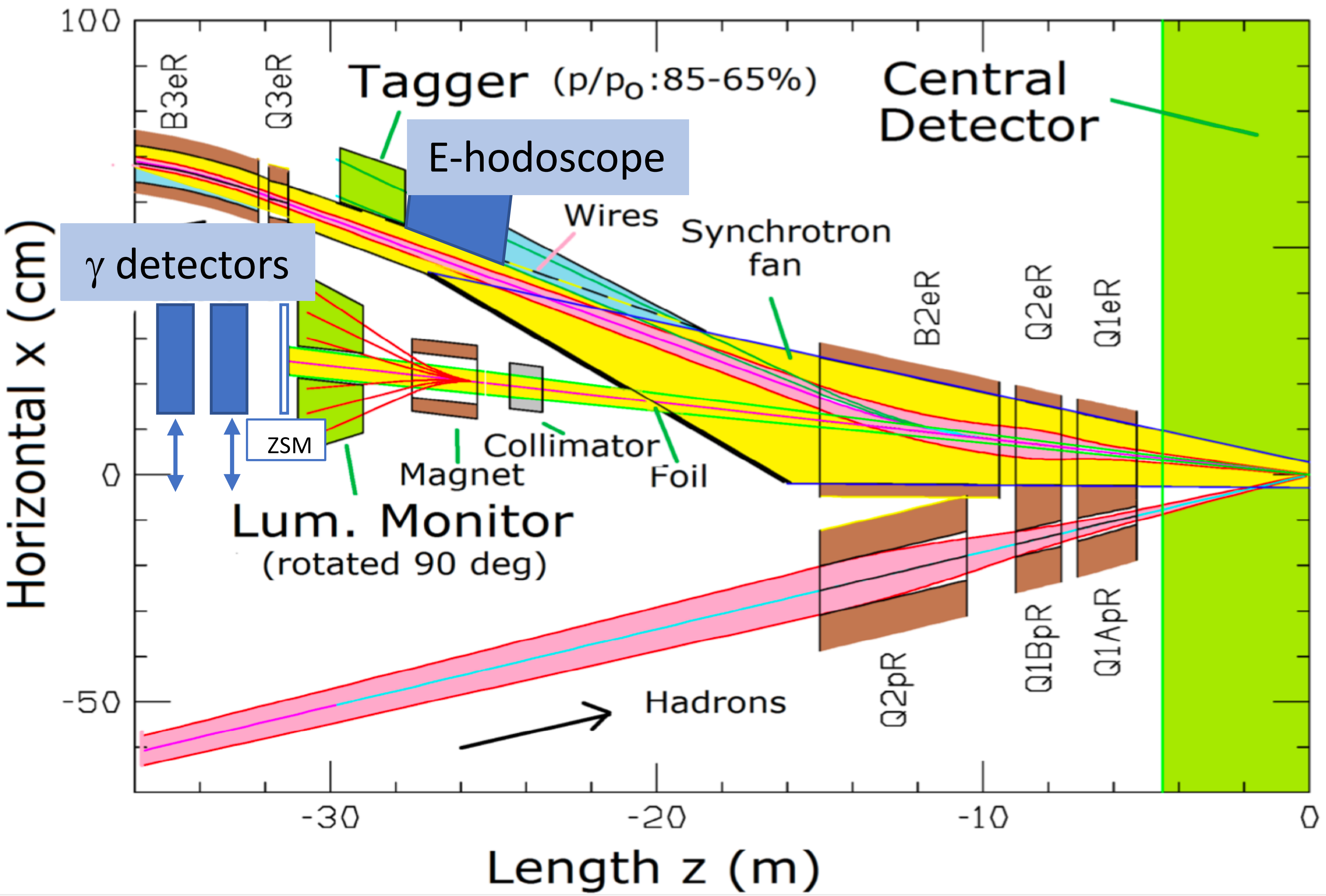




Provisions has been made in the preliminary EIC *Interaction Region* designs for the proper luminosity measurement, as well as for forward electron detectors (photoproduction taggers)

https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf
https://wiki.bnl.gov/eic/

Luminosity measurement & photoproduction tagging



Nota bene: Coherent bremsstrahlung will play a major role at the EIC – its power might even exceed 1 kW!

Subject of exciting research by itself, might lead to novel and useful beam diagnostics.

https://doi.org/10.1103/PhysRevD.103.L051901

“EIC@IP6” and LUMI consortium

Please indicate the name of the contact person:
Przybycien, Mariusz, AGH University of Science and Technology, mariusz.przybycien@agh.edu.pl

Please indicate all institutions collectively involved in this subsystem interest:
AGH University of Science and Technology (AGH UST), Krakow, Poland
Brookhaven National Laboratory (BNL), Upton, USA
Institute of Nuclear Physics, Polish Academy of Sciences (IFJ PAN), Krakow, Poland
Temple University (TU), Philadelphia, USA

Are you interested in joining a new consortia towards a new EIC experiment at IP6:
Yes

Are you interested in actively participating in the detector proposal preparation for a new EIC experiment at IP6:
Yes

Please indicate the items of interest for potential equipment cooperation:
- Subsystem 1:
  - Bremsstrahlung Calorimeters
- Subsystem 2
  - Converted Photons' Detectors (spectrometer system)
- Subsystem 3:
  - Rear Electron Detectors (photoproduction tagging)

https://indico.bnl.gov/event/10825/

Last Friday formation of “EIC@IP6” Collaboration started!

Deadline for its Detector Proposal is **December 1, 2021**

This is for real now – EIC Project budget for 2021 is $30 million (its total is about $2 billion)

https://www.bnl.gov/eic/CFC.php

EIC Conceptual Design Report – February 2021

https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

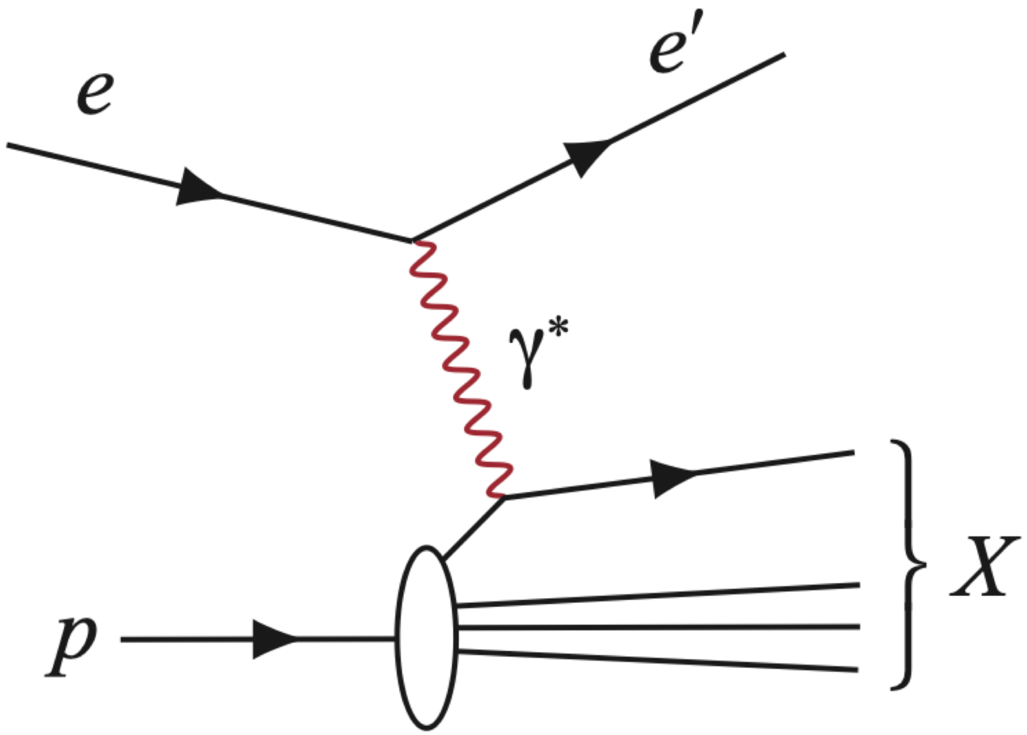
https://wiki.bnl.gov/eic/

Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	93/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0	4.2	1.1
Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	

Beam angular divergence at the I.P. of about **200 μrad** provides the ultimate limit for the p_T resolutions

This is for *ep* collisions, in case of heavy ions, as *eAu* collisions, both CM energy and luminosity **per nucleon** is about 40% of *ep* one

Changing EIC to PIC: Photon-Ion Collider



For very forward scattered electrons the exchanged photons are *quasi-real:*

$$Q^2 \simeq Q^2_{min} + E_e E'_e \theta_e^2 = Q^2_{min} + p_T^2/(1-y)$$

where familiar $Q^2_{min} \simeq m_e^2\, y^2/(1-y)$ and $1-y = E'_e/E_e$.

If we **tag photoproduction**, that is, we catch such scattered electrons for $0.6 < y < 0.9$ and $\theta_e < 3$ mrad then $Q^2_{min} \approx 10^{-7}$ GeV^2 and $Q^2_{max} \approx 2.10^{-3}$ GeV^2 for 18 GeV beam energy.

From previous discussions – the corresponding **impact parameters are much larger than the proton size**, as $m_p/m_e \gg 1$.

Why need photoproduction tagging? It is **restrictive** – why not enough that we **do not see** the scattered electron?

For cleaner selection, if one efficiently kills accidental coincidences (bremsstrahlung!), using mostly timing information

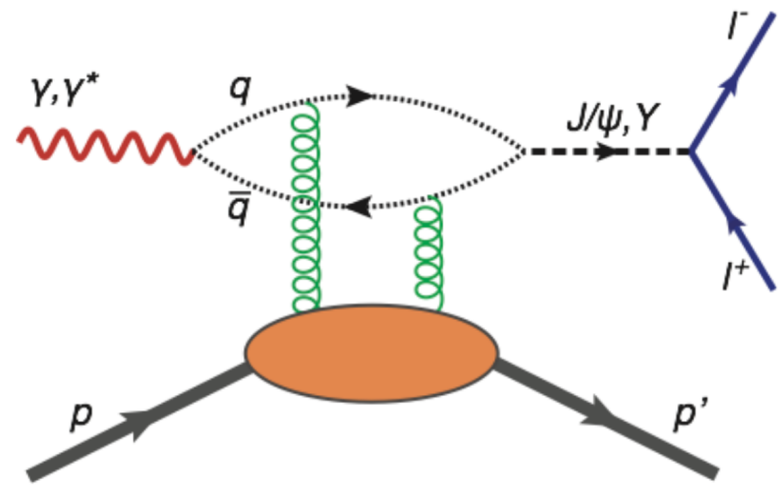
For better kinematical reconstruction, for example essential for σ_{tot} measurements, as for the untagged samples we know only that $Q^2_{max} \lesssim 1$ GeV^2 and γ-ion CM energy (unless it is an exclusive production, and a proton/ion is detected) is poorly controlled. Reminder: the scattered electron p_T has intrinsic resolution limit of about 5 MeV/c.

Changing EIC to MIC: Meson-Ion Collider

According to *Vector Dominance Model* (VDM), photons interact hadronically by fluctuating into neutral vector mesons ($V = \rho, \phi, J/\psi, \Upsilon$…) prior to such interactions.

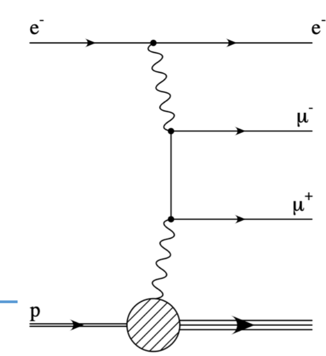
Particularly interesting (remember large impact parameters, microscopically) are exclusive, *quasi-elastic* scatterings, like: $\gamma p \to V p$, or in general $\gamma A \to V A\ (A^*)$.

Nota bene: The **complete** final state could be detected at the EIC – opening possibilities of building various interesting correlations (including azimuthal degrees).



Inelastic reactions, $\gamma p \to V X$, **require tagging**, esp. for high-p_T meson scattering – note that M_X could be determined from electron-meson kinematics.

Finally, two photon (lepton) pair production will be studied. In particular, for the Z^2 enhanced electron-ion case. Tagging is relevant **only** for the electron **calibration**?



Origin of the proton mass

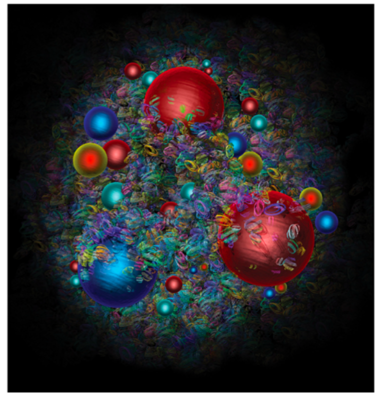
EIC's central aim is to understand better nucleon's internal structure.

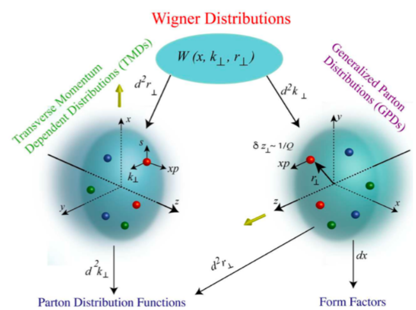
This has various aspects:

- how the quarks and gluons move inside the nucleon,
- 3D imaging of the nucleon – "hadron tomography",
- role of gluons and their emergent properties,
- how is spin decomposed,
- origin of nucleon mass,
- . . .

Lattice can provide *qualitative* and eventually *quantitative* knowledge of different functions and their moments:

- 1D: form factors
- 1D: parton distribution functions (PDFs)
- 3D: generalized parton distributions (GPDs)
- 3D: transverse momentum dependent PDFs (TMDs)
- 5D: Wigner function





At the physical point, the quark and glue energy contributions are 32(4)(4)% and 36(5)(4)% respectively. With the quark scalar condensate contribution of 9(2)(1)% [4], we can obtain that a quarter of the trace anomaly contributes 23(1)(1)% with $N_f = 2 + 1$.

https://doi.org/10.1103/PhysRevLett.121.212001

Proton Mass Decomposition from the QCD Energy Momentum Tensor

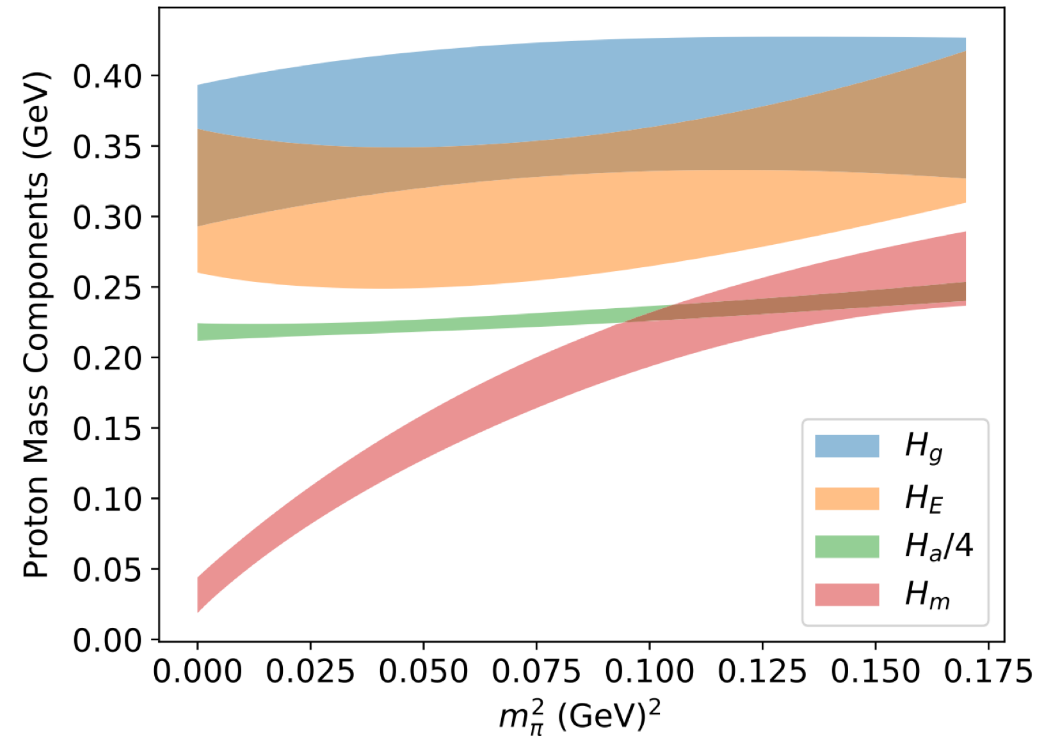


FIG. 3. The valence pion mass dependence of the proton mass decomposition in terms of the quark condensate $\langle H_m \rangle$, quark energy $\langle H_E \rangle$, glue field energy $\langle H_g \rangle$, and trace anomaly $\langle H_a \rangle/4$.

From the Cross section to the Trace Anomaly

D. Kharzeev. Quarkonium interactions in QCD, 1995

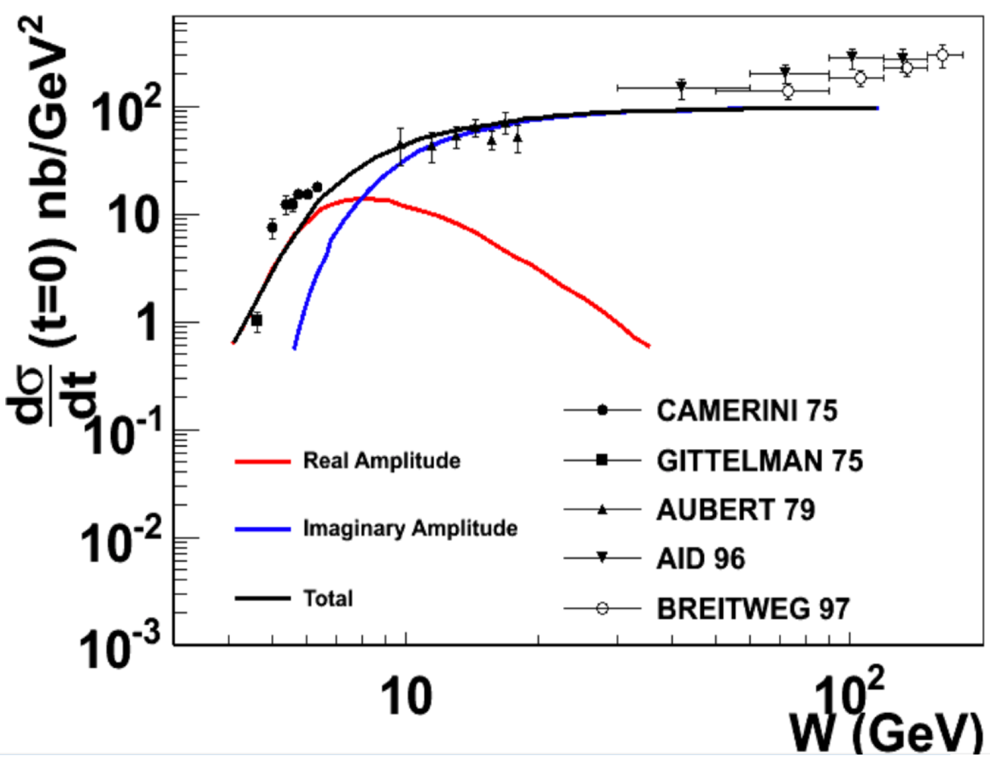
D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, Eur.Phys.J., C9:459–462, 1999

$$\frac{d\sigma_{\gamma N\to\psi N}}{dt}(s,t=0) = \frac{3\Gamma(\psi\to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2 \frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)$$

$$\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0) = \frac{1}{64\pi}\frac{1}{m_\psi^2(\lambda^2-m_N^2)}|\mathcal{M}_{\psi N}(s,t=0)|^2$$

- VMD relates photo-production cross section to quarkonium-nucleon scattering amplitude $M_{\psi p}$
- **Imaginary part** is related to the total cross section through optical theorem
- **Real part contains the conformal (trace) anomaly**
  - Dominate the near threshold region and constrained through dispersion relation

A measurement near threshold could allow access to the trace anomaly



Summary & outlook

Precise luminosity measurements are very challenging at the EIC – both the absolute and relative ones – **many open issues** to address (before Dec 1), apart from pure detector aspects:

- Is a 0.5% absolute luminosity precision enough – do we profit in some physics analysis from yet a better one – only inclusive pdf measurements, or some exclusive processes would profit too? What about beam polarization errors?
- What are theoretical uncertainties of the bremsstrahlung BSE and HO corrections?

Efficient detection of very forward scattered electrons is a very powerful tool, effectively turning the EIC into high energy photon-ion collider – **many open issues** to address (before Dec 1), apart from pure detector aspects:

- What electron p_T and energy resolutions are required for physics? Are electron azimuthal correlations interesting, at sufficiently high electron p_T?

Thank you!

Basic research is what I am doing when I don't know what I am doing.

-- *Wernher von Braun*

Extra slide

TABLE V. Numerics for the sum rule in Eq. (51) for one-loop, two-loop, and three-loop analyses. All the results are in units of GeV. (See caption of Table II for more details.)

		$O(\alpha_s^1)$	$O(\alpha_s^2)$	$O(\alpha_s^3)$
Scenario A	M_q	0.311 ± 0.053	0.309 ± 0.053	0.309 ± 0.054
	M_m	0.073 ± 0.078	0.073 ± 0.079	0.074 ± 0.080
	M_g	0.554 ± 0.027	0.556 ± 0.028	0.555 ± 0.028
Scenario B	M_q	0.220 ± 0.017	0.216 ± 0.017	0.215 ± 0.017
	M_m	0.183 ± 0.022	0.185 ± 0.023	0.187 ± 0.023
	M_g	0.535 ± 0.012	0.538 ± 0.012	0.536 ± 0.012

https://doi.org/10.1103/PhysRevD.102.114042

The impact of including a sigma term for charm quarks, that is, going from Scenario A to Scenario B, is clearly visible for all the sum rules. In the first place, by definition, this switch affects the quark mass term M_m of the sum rule in Eq. (51)—see Table V for the corresponding numbers. It is often asked how much of the proton mass can be attributed to the Higgs mechanism. What seems clear is that M_m is entirely due to the Higgs mechanism, as this contribution would vanish if the quark masses were zero. In that case, the entire mass of the proton could be associated with either the gluon contribution to the trace anomaly, or the sum of what we have called the quark and gluon energies. In Scenario A, less than 10% of the proton mass are due to the Higgs mechanism, while in Scenario B, this number is close to 20%. Also, it is known that the numerical values for the sigma terms of the charm, bottom, and top quarks should be similar, which can be derived using a heavy-quark expansion [66,70]. This is compatible with lattice results according to which the heavy-quark condensate $\langle(\bar{\psi}\psi)_R\rangle$ behaves like $1/m_Q$ for quark masses m_Q larger than about 500 MeV [64]. A direct calculation of the expectation value $\langle(F^{\alpha\beta}F_{\alpha\beta})_R\rangle$ could provide further information about the role played by the Higgs mechanism for the numerics of the proton mass decomposition.